Evaluation and optimization of district energy network performance: Present and future

Q5

The corrections made in this section will be reviewed and approved by a journal production editor.

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Abstract

The building sector accounts for the largest portion of total final energy consumption in most countries, and is responsible for around one third of carbon emissions, which have been regarded as the cause for global warming and climate changes. District energy network, which can supply consumers with heating/cooling and electricity, is an effective and proven approach to enhance energy efficiency and reduce carbon emissions. Currently, the approach of integrated energy systems (including renewable energy) tends to be increasingly necessary and significant for the district energy network. This article presents a comprehensive review of energy performance of district energy networks, focusing on optimization and evaluation of district heating network combining with other relevant energy systems and renewable technologies. This review consists of the concept of district energy network, typical applications of district energy network, and significant literatures of energy performance of various energy networks based on theoretical modelling and analysis, physical experimental studies and numerical simulations. Furthermore, over 30 factors affecting energy performance have been substantially investigated and assessed. This review has demonstrated that main effects on energy network performance are significantly linked to configurations and capacities of system, climate conditions (locations and time), and the interaction between various factors. An optimal overall performance of district energy network would need to integrate several advanced energy systems, e.g. a balanced energy network.

Keywords: District energy network; Heating systems; Parametric analysis; Numerical modelling; Energy performance; Evaluation and optimization

1 Introduction

In most countries, the building sector constitutes over 30% of total final energy use and an equally important source of carbon emissions [1]. Similarly, across the world, the domestic building sector is responsible for around 40% of the final energy consumption and around one third of carbon emissions, which has been regarded as a cause of global warming and climate changes [2,3]. The “Climate Change Act 2008” has set a goal of 80% reduction in greenhouse gas emissions in the UK (taking the 1990 emissions as references) to be reached by 2050 [4]. The enhancing trend towards building and its indirect consumption will insist on following years because of extension of built regions and related energy requirements [3,5].

District energy network (DEN) is a proven and efficient energy solution that has been increasingly applied in cities worldwide. DEN plays a critical role not only in improving energy efficiency of current standard systems, but also in supporting a future trend, i.e, completely 100% renewable energy systems. Apparently, there are significant opportunities for DEN to help achieve energy and CO_2 targets, based on an advanced optimization strategy through integrating renewable energy systems, smart thermal storage and smart grid technologies into this network [6,7].

Research and applications of DEN systems were initiated in USA at the end of 19th century, which were focused on the district heating system (DH) [6]. As shown in Fig. 1, three generations of DH have been developed since 1880s [6, 7]. The concept of fourth generation DH (4GDH) has been established by Lund et al., in 2014 [7]. Currently, some applications of 4GDH or next generation have been implemented since then (see Table 1 [8–19]). More importantly, except for the basic function of supplying heating and cooling, 4GDH can be applied by the combination of conventional energy systems (heating/cooling and electricity), renewable energy technologies (geothermal heat, solar energy, biomass, wind, hydropower etc.), and other relevant technologies such as heat pumps, smart grid, smart heat storage, waste heat recovery and application, etc.

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Fig. 1

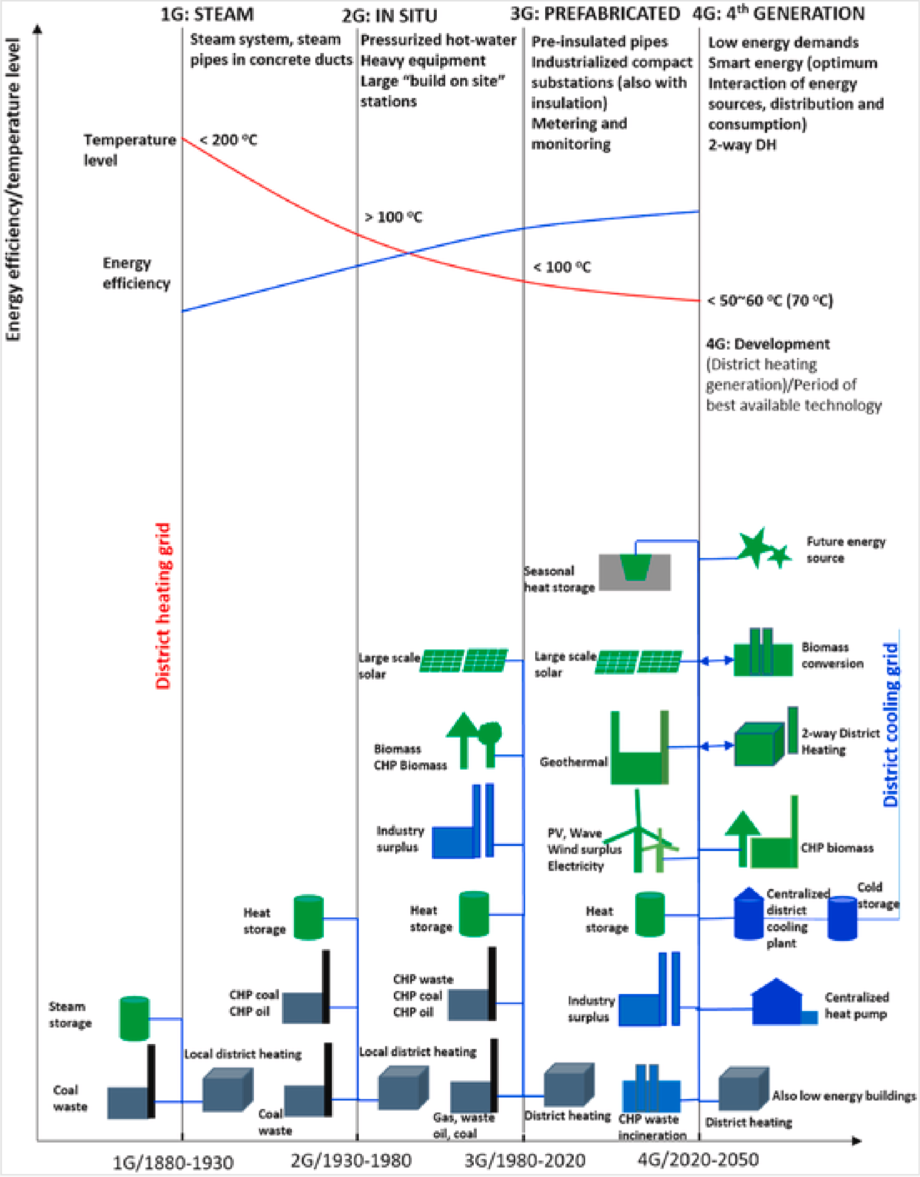

Illustration of development of four generations of district heating networks [7].

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Table 1

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List of the state-of-art applications of district energy network.

Projects	Methods	Benefits	Year	Country & Institution/Company, Research Council	References
Renewable heat networks: modelling for robust design	Operating over wider temperature ranges than 70–95 °C traditionally used, fully coupled solutions to pipeflow hydraulics and thermal energy transport	An object-oriented, fully coupled heat and flow simulation codes for heat networks developed; deep geothermal resources heat networks' design explored	2013–2016	UK, University of Glasgow/Cluff Geothermal Ltd.	[8]
Balanced Energy Networks (BEN)	Balancing of heating/cooling, electricity, and carbon to deliver both a physical and digital network with smart grid technology	Delivering security of supply, at low lost, and with low CO_2 emissions; providing the efficiency benefits of a heat network without the added pollution (no combustion) of energy centres in dense urban areas	2016–2018	UK, ICAX/London South Bank University etc., Innovate UK	[9,10]
Combined Heat and Power (CHP) district energy scheme	State of the art CHP technology; heat and power distributed to campus via large, insulated steel pipes and cables	Reducing carbon footprint and saving costs; 4500 tonne CO_{2e} savings per year; financial savings of £2.6M per year	2015–2018	UK, University of Strathclyde	[11]
Thermal Energy Resource Modelling and Optimization System (THERMOS)	To develop, test and create open-source tools to amplify and accelerate the development of new low-carbon heating and cooling systems, and to enable faster upgrade, refurbishment and expansion of existing systems	To provide public authorities with energy-system mapping methodologies, software and associated modelling tools in order to develop, expand and upgrade district heating and cooling systems far more efficiently and cost effectively than now; to enormously reduce planning costs	2016	UK and EU, Centre for sustainable energy (CSE), Horizon 2020	[12]
LOGSTOR FlextraPipe	Using the best insulation value ($\lambda = 0.0207$ W/mK)in the market	Performance is constant for its entire service life; reducing heat loss between heating plan and consumer regardless of energy form	2017	Denmark, 4DH research centre	[13]
Conversion of existing district heating grids to low-temperature operation and extension to new areas of buildings	Low-temperature (<40 °C) district heating systems based on renewable energy	Such development is fundamental to the implementation of Danish objective of fossil fuel-free by 2050 as well as EU 2020 goals	2012–2016	Denmark, 4DH research centre	[14]
4th Generation	To assess different insulation standards, combining	The pipes with the highest insulation standard	2016	Denmark, Aalborg University,	[15]

District Heating (4DH)	detailed heat loss analysis with integrated energy systems analysis, to supply the input for decision support	available currently might be preferable in future if investment costs reduce or fuel prices increase		Innovation Fund Denmark	
Minibems	Employing state-of-the-art controls to manage remotely, monitor users' energy usage, diagnose faults without visiting site	To achieve 25% built in energy-saving across the entire heat network; making heat network visible; significant energy reductions and cost savings e.g. relatively low outlay for installer and customer	2017	UK, University of Exeter, Department for Business, Energy & Industrial Strategy; Innovate UK & Shell	[16]
Stakeholder Interactive City Energy Demand Simulator (SiCEDS)	To use the simulator to compare the cost and impact of diverse technologies e.g. solar PV and insulation schemes etc.; one complete digital model of energy systems for one city including buildings, transport, heat demand, local generation and distribution etc.	SiCEDS is most beneficial for strategic planners to assist cities to meet the ambitious sustainability, air quality and self-sufficiency plans; District Network Operator (DNO) companies can explore ways to better manage power demand in cities	2016–2017	UK, UCL and Energy Saving Trust; Innovate UK	[17–19]

In the past years, there have been several review papers on the district heating systems [20], the status of 4G district heating [21], district heating and cooling [22], and future district heating systems and technologies etc. [23]. Mazhar et al. did an overview from economic and social aspects of district heating, presented the legislation, technological framework and policies with linkage to basic characteristics of grids [20]. Lund et al. described the contemporary developments and findings relevant to different elements required in the future 4G district heating systems [21]. The key point for the future 4G generation district heating is to determine a safe margin for ensuring benefits exceeding costs via integrating district heating into the future renewable energy sources, which is playing an important role in achieving the sustainability, and smart energy system. Werner reviewed the current conditions of district heating and cooling, particularly providing deeper insights into European situation, from the point of view of supply, technical, market, institutional, environmental, and future contexts [22]. The review results illustrate that there are obvious potentials to have viable supply options for district heating/cooling systems in the future. Lund et al. focused on an important role of next-generation district heating systems and technologies [23]. Currently, primary challenge is to understand the implementation of above systems and technologies and to need the legal framework.

However, there is few review papers on the district energy networks (DEN), particularly their performance evaluation and optimization; meanwhile, there is almost no studies to review parametric sensitivities of parameters analyzed to justify overall performances of these energy networks.

The objective of this article is to comprehensively review the energy performance of district energy networks, focusing on optimization and evaluation of district heating network combining with other relevant energy systems and renewable technologies. First, the concept of district energy network was introduced. Second, several typical applications of this network were reviewed to demonstrate the state-of-the-art technologies. Third, performances of various energy networks were evaluated and discussed in terms of theoretical modelling, physical experiments, and numerical simulations. Thus, parametric sensitivities of over 30 parameters were analyzed to justify overall performances of these energy networks. Finally, conclusions with key findings and future works were also presented.

2 District energy network

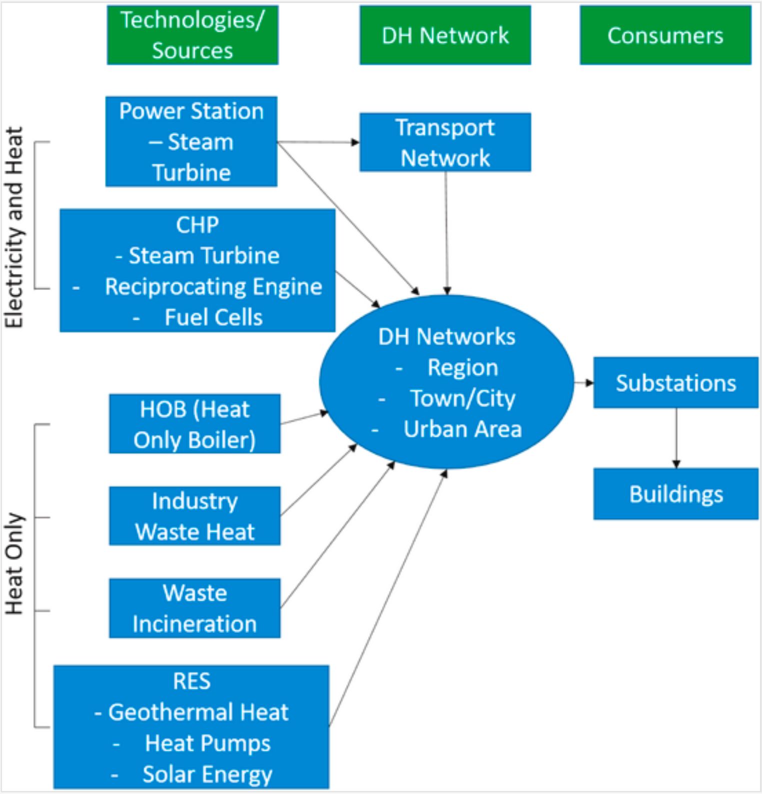
District energy network (DEN) can provide building users with thermal energy and power from centre plants of energy generation, in a form of heating/cooling and electricity. It is widely applied in urban areas, including residential, commercial and industrial buildings. The following benefits can be achieved using DEN: 1) apart from the conventional installation of heating or cooling plants in individual building, it is a new solution of energy supply which can apparently reduce capital costs for building owners; 2) it would save more spaces for conducting main functions/activities of the building; 3) it would improve the potential to introduce more renewable energy sources in a larger scale of a region; 4) it could encourage more applications of advanced energy-effective technologies such as CHP, smart thermal storage, etc. [7].

District heating network (DHN) is the most common type of DEN [7]. Lund et al. [7] has reviewed and assessed three previous generations of DHN, such as 1G: from 1880 to 1930, 2G: from 1930 to 1980, 3G: from 1980 to 2020, and defined the concept of the fourth generation of 4G: 2020–2050 (Fig. 1).

District heating system including sources, network and consumers is just presented using schematics below (Figs. 1 and 2). There have already been some existing district energy networks applied around the world below (Figs. 3–5). Some investigations have comprehensively studied and discussed the trends and developments of the four generations of district heating [6,7,24]. In this article, all those abovementioned contents will be not introduced and reviewed again.

alt-text: Fig. 2

Fig. 2



Components and workflow chart of district heating system [6].

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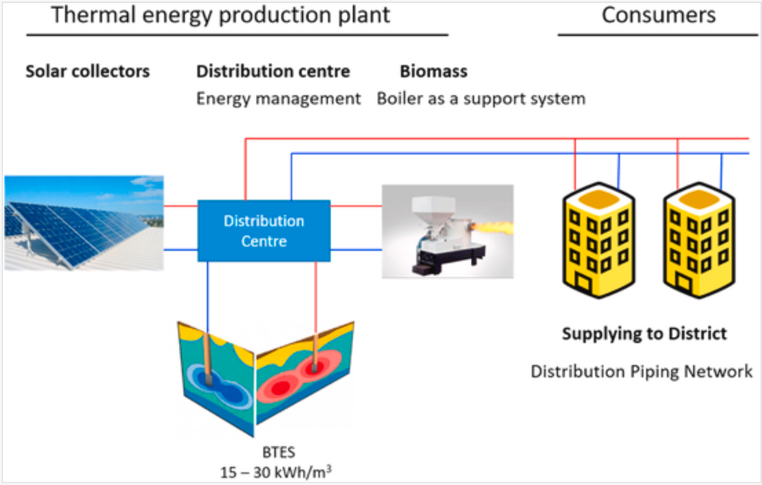
Fig. 3



Scheme of district heating system: Solar District Heating system with underground thermal energy storage [25].

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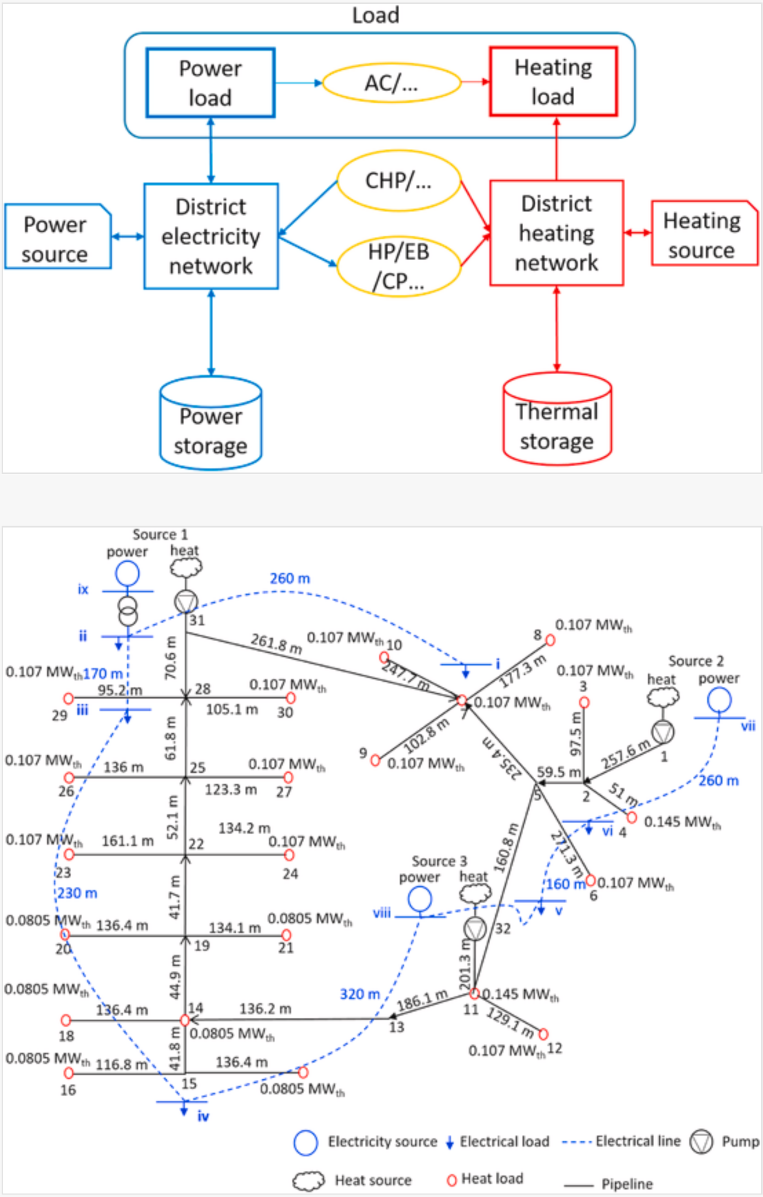
Fig. 4



(a): Structure of district electricity and heating network [26]. (b): Schematic diagram of district heating and electricity network of Barry Island [26–28].

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Fig. 5

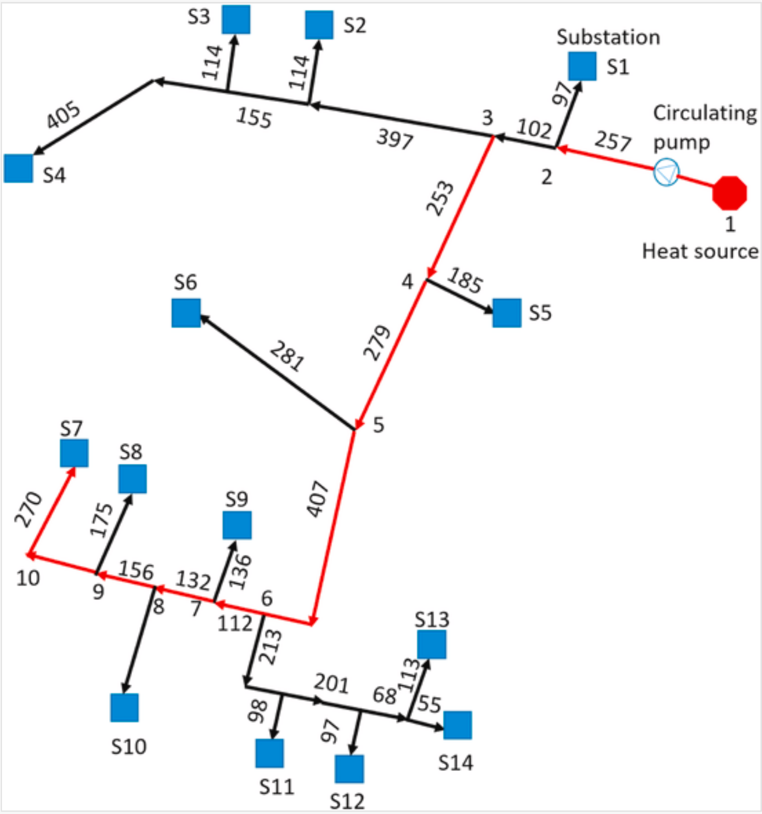

Diagram of an existing indirect district heating network in Hohhot, Inner Mongolia, China [29].

3 Methods

3.1 Review methodology

The literature selected in this work mainly derived from the following databases: *Web of Science*, *Scopus*, *Science Direct*, *Research Gate* and *Google Scholar*. Main keywords for the review were selected to determine the suitable scientific papers including three categories: “district energy network performance”, “evaluation” and “optimization”. The following search strings based on the above keywords have been employed in the aforementioned databases – [(“district energy network” OR “district heating” OR “district energy network performance”) AND (“evaluation” OR “assessment” OR “performance evaluation” OR “performance assessment”) AND (“optimization” OR “performance evaluation” OR “optimal”)]. The Boolean search terms AND and OR have been applied to incorporate different combinations aiming to obtain the suitable literature for the review.

In this review, as shown in Table 2, a detailed summary of recent DEN models and their energy performances has been demonstrated.

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Table 2

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Summary of DEN models and relevant studies reported in literatures.

Publications/References	Objectives and Method Used	Types of Heat/Energy Networks	Software/Model Used	Controlled Objects/Variables	Special Findings
THERMOS 2016 [12]	To develop and propose a state-of-the-art methodology for developing address-level energy systems maps	Low-carbon heating and cooling networks	Digital surface model (DSM)	Thermal energy system planning	Developed methods, data, and tools could provide sophisticated thermal energy systems planning far more cheaply and rapidly than now
4DH research centre [13,15,45]	Best insulation value of pipe with complete diffusion barrier	Heating network	LOGSTOR calculator	Insulation value	The use of energy resources have to be diligent and efficient
Pahud et al. [46]	Several ground layers with different thermal properties specified within storage region;	Heating network	TRNSYS, Duct ground heat storage model	Dimensions; thermal properties of ground layers	All the array dimensions are set in "include file", which let it easier to adjust and check their dimensions
Mohammadi 2016 [14]	To evaluate the feasibility of implementing alternative design concepts and strategies in the move towards low-temperature district heating	Low-temperature heat network (4DH)	Matlab, thermal-dynamic modelling; TERMIS; EnergyPLAN; Heat Atlas	Flow and temperature distribution through the network, heat losses in the grid, bypass heat losses, return temperature to the plant	New configuration for bypass application in district heating system to shrink losses has been proposed
Lund et al., 2016 [15]	To introduce a methodology, which can describe the balance between cost of pipe insulation and associated savings of heat supply system, for a specific case and its application in Denmark	4th Generation DH	Matlab, EnergyPLAN model	Heat supply temperature, pipe length, pipe inner and outer diameter, insulation thickness, soil temperature, heat load, consumers return temperature, bypass points, bypass set-point temperature, generating network connection matrix	The pipes with the highest insulation standard available now might be preferable in future if fuel prices increase or investment costs reduce
Lomax et al., 2017 [17]	To help one produce, compare and develop variable approaches to energy consumption, generation and distribution affecting air	City energy network	SiCEDS simulator	Approaches to energy consumption, generation and distribution, technology	The outputs of SiCEDS could be viewed in time series charts, maps and exported as

	pollution, carbon emissions, health and fuel poverty; to be a powerful tool for developers, planners, community groups & investors; to enhance the efficiency with which diverse local energy and transport demand scenarios produced and shared			schemes, source of heating, number of build properties, heat load density threshold, proportion of heat delivered, efficiency of solar PV, transport load factor	tables in order to analyse further in future
Zheng et al., 2017 [47]	To compare function method to node method for dynamic temperature simulation of district heating network	DH network	Dynamic model, physical model	Environment temperature,	Function method is more precise than node method for the quick dropping stage and relatively stable stage; calculation time of function method is decreased by around 37% compared to node method
Safa et al., 2015 [36]	To develop cooling/heating performance curves according to building loads and source temperatures	Heating network with GSHP	TRNSYS, Physical experiment	outlet temperature of condenser	Lower ground temperature around the loop will resulting in deteriorating slightly the performance of GSHP
Sartor et al., 2017 [48]	To model heat transfer in pipes in district heating network considering thermal losses and pipes' inertia	DH networks	Proposed modelling method based on TRNSYS Type 31	Pipe thickness, thermal inertia of the pipe, heat loss	Pipe's thermal inertia has an obvious impact on outlet pipe temperature response, particularly when a morning boost of the network
Vesterlund et al., 2017 [49]	To minimize the whole operating costs related to the heat generation at multiple production sites and its delivery to end users; a hybrid evolutionary-MILP algorithm developed and coupled to DH network	DH network	Simulink	Pumping power, level of complexity, pumping power	Optimal supply temperature is the lowest compatible with the service to end users to decrease as much as possible thermal losses along distribution network
Pirouti et al., 2013 [50]	To minimize annual total energy consumption and	DH network	PSS SIGNAL, FICO Xpress	changing temperature limit, DH operating	Annual total energy consumption

	costs using optimization strategies		optimization suite	strategy, pipe diameters, heat source, flow rate of the heat carrier, temperature difference between supply and return pipes	and equivalent annual cost will decrease with increasing temperature difference between supply and return pipes
Ghadimi et al., 2014 [32]	To evaluate the value of integrated system sizing and operational strategy selection	CHP DH network	Matlab: Generic modelling of CHP system, FMINCON application	Operational constraints, transient characteristics of CHP system	On-off operational method would result in a lower NPV and a higher environmental effect, although it could minimize surplus energy generation
Vesterlund et al., 2015 [51]	To propose a new process integration method to model complex district heating system which contain loops	District heating systems (DHS)	Simulink, reMIND software, CPLEX	Loops and bottlenecks	The proposed method offers opportunities to redesign DHS in future without considering artificial changes to the model structure
Wang et al., 2015 [33]	To place the peak boiler somewhere to make the overall costs the smallest.	CHP DHS	Multicriteria decision analysis (MCDA) model	Power load, locations of peak heating	The economic optimal peak boiler would be placed at the CHP plant with cheaper “self-use electricity” in CHP in order to distribute the heat
Fang et al., 2015 [52]	To apply genetic algorithm to optimize fuel and pumping costs for arbitrary district heating networks with multiple heat plants	DH network	Matlab, Genetic algorithm	Pumping costs, supply temperature	The production has been simultaneously optimized at multiple plants at different locations of the district heating network
Jie et al., 2015 [29]	To develop four strategies for the minimum pumping cost and heat loss cost (PHLC) using optimization model	DHS	Matlab	DHS operating strategies, heating parameters, outdoor temperature, supply temperature	The strategy of controlling primary and secondary water flow rates at the same time would obtain the minimum PHLC compared to other three

					strategies; the limit of pump frequency should be considered if employing the proposed optimization model to engineering practice
Carpaneto et al., 2015 [39]	To optimize and find out the best method for sizing proportions of conventional sources and solar, and in order to define the optimal storage capacity	DH network integrating solar energy	Matlab	The tilt angle and meteorological reduction factor	The proposed approach could highlight the solar inputs' advantages, particularly reducing the management costs during mid-season periods and summer while the use of boilers can be replaced by almost-zero marginal cost thermal energy
Wang et al., 2016 [53]	To propose a novel matrix simulation model, which is easy to add or change new components, in order to increase the overall energy efficiency of the heat supply	DH systems	Matlab: Genetic Algorithm	Thermal and delaying effects of pipes	The more CPU-time and observed data, the better calibrated model; the number of uncertain parameters could be obviously decreased through model parameters aggregation
Mertz et al., 2016 [54]	To propose a tool as DH network's design assistance, to minimize total cost of DH network over 30 years	DH network	Mixed integer non-linear programming (MINLP) model, DICOPT solver	Supply and return pipe	Results confirm the importance for optimizing configuration and design at the same time
Li et al., 2016 [34]	To propose a combined heat and power dispatch (CHPD) model solved by the iterative method considering DH network's temperature dynamics	DH network with CHP	Matlab, IPOPT solver	Dynamics of temperature variation	The proposed CHPD method could enhance overall economic efficiency of CHP system, provide more operation flexibility and facilitate higher

					wind power accommodation
Pan et al., 2016 [26]	To study interactions in a district electricity and heating system considering time-scale characteristics	Integrated district electricity and heating systems	Matlab	Heat from radiators to indoor air, thermal and hydraulic processes, coupling component outage	Attention should be on the slow thermal process and quick hydraulic process for total economic operation and system security
Liu et al., 2016b [31]	To model and assess three networks in an integrated manner	Integrated electricity-heat-gas networks	Matlab-Excel VBA, Newton-Raphson approach	different conversion components	The case studies illustrate clearly how varying supply technologies at diverse levels in district strikingly influences multi-energy flows in the integrated three networks and then cash flow and emission balances
Falke et al., 2016 [55]	To develop the multi-objective optimization model applied in a district of medium-sized town and to investigate effects of diverse efficiency measures considering total costs and emissions of CO_2 equivalents	Distributed energy network	Multi-objective optimization model	different efficiency measures	Mathematical complexity problem could be solved through decomposing it into three stages: district heating network design, generation units design and generation units operation simulation
Morvaj et al., 2016a [56]	To study the optimal design, distributed energy systems operation, optimal heating network layouts	DH network	Mixed integer linear programming model, ε-constraint method	Constraints	The proposed district heating system could deliver emission savings of 23% over a standard solving method based on the same cost
Morvaj et al., 2016b [30]	To present a novel optimization framework combining optimal design and distributed energy systems operation considering calculations	Districted energy systems with electrical grid	Matpower in Matlab, Newton-Raphson method; EnergyPlus	Electrical grid constraints,	Inclusion of grid constraints in operation scheduling decreased 18%

	of building energy use and grid constraints				carbon emissions
Vesterlund et al., 2016 [57]	To investigate the flow distribution in DH network with a meshed structure for a town of Kiruna in Sweden	Meshed DH network	Matlab/Simulink	Expansion and demolitions, thermal losses, addition of other heat production sites	The biggest drops in temperature and pressure of the heat production site to nodes under major consumer areas are within 9 °C and 1.2 bar in days of the highest demand
Comodi et al., 2017 [35]	To analyse possible technical improvements of CHP-DH in the Mediterranean areas	CHP-DH network	Physical measurement	Management strategies, energy price changes during its lifetime	Lowering DH water operating water could decrease around 7% thermal losses
Lizana et al., 2017 [25]	To investigate the application of biomass and solar district heating system in Mediterranean areas with low-to-moderate population density	DH systems with low-carbon energy technologies	Cost model, Sensitivity analysis	Linear heat density (LHD)	It would be viability with internal return rates higher than 9.8% and 7.4%, and payback period within 10 and 13 years, for biomass and solar systems, respectively, if the linear heat density is greater than 1.5 MWh/m
Sheng et al., 2017 [58]	To analyse the factors influencing energy saving rates in distributed variable-frequency speed pump DHS and find out a better design reference	DHS	Mathematical model	Efficiency of variable speed regulator	For the case with one heat source and case with seven heat sources, the calculated results and measurement data illustrate maximum electrical energy saving are 49.4% and 40.5%
Pan et al., 2017 [59]	To propose a new feasible region method for formulation of new DHS models which could exploit DHS flexibility considering building thermal inertia	DHS	Matlab	Operation constraints, storage matrix	Proposed method is effective in facilitating integrated electricity and heat dispatch and making the dispatch scalable,

					acceptable and extensible.

There are four methodology types of investigations into performance of DEN as follows, shown in Fig. 6:

a) Theoretical modelling.

b) Numerical simulations using Matlab/Simulink, TRNSYS etc.

c) Physical experiments.

d) Parametric sensitivity studies.

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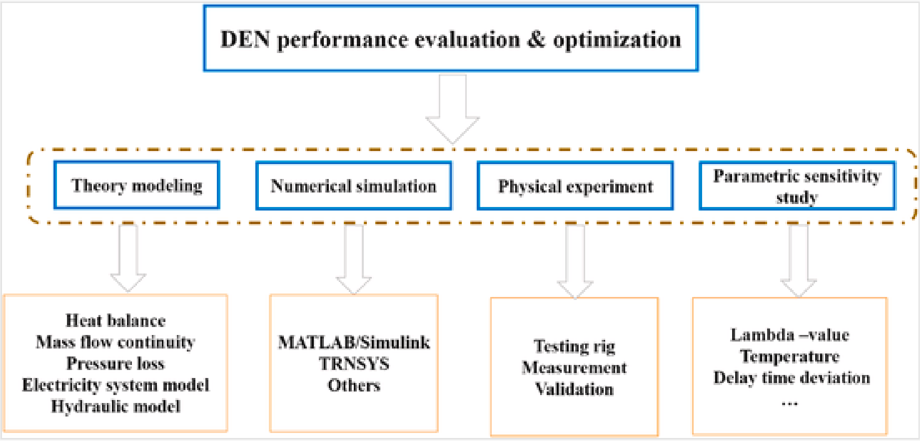
Fig. 6



Flowchart for the methodology of DEN performance investigation.

Table 2 presents two main types of DEN, categorised by the system configurations including district heating (DH) network and DH network integrated with other networks. The latter includes electricity [26,27,30,31] and gas [31], and other technologies e.g. CHP [32–35], GSHP [9,30,36–38], and renewable energy technologies including solar energy [17,25,39–43], geothermal energy [44], biomass [25] etc.

4 Results

4.1 Representative projects

As mentioned earlier, Table 1 lists a series of representative state-of-art projects integrating various types of low carbon and renewable energy technologies into district energy network in recent years. Those projects have been mainly come from and funded by the UK and EU countries. Table 1 is illustrating the project name, methods, benefits, the period of project, and country as well as research institution/company and research council. Seen from Table 1, the investigated scale is including from the building(s) scale to the urban scale; the used advanced technologies have renewable energy technology, fully coupled solutions, balancing heating/cooling and electrical energy source supply, storage, distribution and application with smart grid technology including demand side response (DSR) etc., super insulated pipes (Flextra) and cables, low temperature heat network, state-of-art remote control, monitoring and management, complete digital model; the study methodologies cover physical experiment, numerical simulation/modelling and programming/coding.

The next generation district energy network – balanced energy network (BEN) [9] has been recently built in authors' university campus in London, UK. It combines cold water heat network (its temperature level approaches to underground water temperature 14 °C, which is far less than 4th generation DHN 50–60 °C and it could then decrease heat losses via pipeline transfer, see Fig. 1) with the smart-grid technology to balance the production of heating, cooling and electricity so as to minimize carbon emissions and costs. BEN consists of several advanced technologies e.g. borehole, cold water heat networks, water source heat pump, smart thermal storage, demand side response (DSR) strategy, and two buildings in the campus.

4.2 Mathematical modelling

Many mathematical models for district energy networks have been presently proposed in literature. This section categories them in following (1) heat balance [26,60,61], (2) continuity of mass flow [34], (3) pressure loss [34,57,62], (4) electricity system model [26,33], and (5) hydraulic model [26,27,61,63–65].

4.3 Heat balance

Jie et al. [29] investigated indirect district heating (IDH), which has three types of heat balance conditions. First, heat supply during a period of time equals heat demand and heat loss for the heat pipelines buried in the ground, which is shown as follows.

$$\int_0^\tau Q_s dt = \int_0^\tau \left(Q_d + Q_{lp} + Q_{ls}\right) dt \tag{1}$$

$$Q_{lp} = 10^{-3}\left(1+\beta\right)\left[\begin{array}{c}\sum_{i=1}^{n} \frac{(t_{ps}-t_g)(R_{b2i}+R_{ti})-(t_{pr}-t_g)R_{ci}}{(R_{b1i}+R_{ti})(R_{b2i}+R_{ti})-R_{ci}^2} l_i + \\ \sum_{i=1}^{n} \frac{(t_{pr}-t_g)(R_{b1i}+R_{ti})-(t_{ps}-t_g)R_{ci}}{(R_{b1i}+R_{ti})(R_{b2i}+R_{ti})-R_{ci}^2} l_i\end{array}\right] \tag{2}$$

$$Q_{ls} = 10^{-3}\left(1+\beta\right)\left[\begin{array}{c}\sum_{j=1}^{m} \frac{(t_{ss}-t_g)(R_{b2j}+R_{tj})-(t_{sr}-t_g)R_{ci}}{(R_{b1j}+R_{tj})(R_{b2j}+R_{tj})-R_{cj}^2} l_j + \\ \sum_{j=1}^{m} \frac{(t_{sr}-t_g)(R_{b1j}+R_{tj})-(t_{ss}-t_g)R_{cj}}{(R_{b1j}+R_{tj})(R_{b2j}+R_{tj})-R_{cj}^2} l_j\end{array}\right] \tag{3}$$

where Q_s is heat supply in kW, Q_d is consumers heat demand in kW, Q_{lp} is primary heating network heat loss in kW, Q_{ls} is secondary heating network heat loss in kW, τ is a period of time in s, β is coefficient of additional heat loss caused by compensators, valves, accessories. t_{ps} is primary supply water temperature in °C, t_g is ground surface temperature in °C, R_{b1} and R_{b2} are the heat resistance for insulation materials of two parallel pipes (i.e. supplying and return water pipelines) buried in the ground in m °C/W, R_t is the ground heat resistance in m* °C/W, t_{pr} is primary return water temperature in °C, R_c is additional heat resistance in m* °C/W, l is the pipe length in m, t_{ss} is the secondary supplying water temperature in °C, t_{sr} is the secondary return water temperature in °C, i and j are the pipe sections number with the same diameter in primary and secondary heating networks, respectively, n and m are total account of pipe sections with the same diameter in primary and secondary heating networks, respectively.

Second, the heat transfer process within heat exchangers for the secondary heating network could be presented:

$$\int_0^\tau K_h A_h \Delta t_m dt = \int_0^\tau \left(Q_d + Q_{ls}\right) dt \tag{4}$$

where K_h is heat exchanger's heat transfer coefficient in W/m^2*°C, A_h is heat exchanger area in m^2, Δt_m is the logarithmic mean temperature difference in °C.

Third, for consumers, heat transfers via radiators to each room. The heat balance for radiators could be defined below:

$$\int_0^\tau 0.001 n_s a_s \left(\frac{t_{ss}+t_{sr}}{2} - t_n\right)^{b_s} dt = \int_0^\tau Q_d dt \tag{5}$$

where n_s is pieces of radiators, a_s and b_s are calculating heat transfer coefficients from one piece of radiator to rooms, t_n is indoor temperature in °C.

Both of buildings and DH systems have the properties of thermal storage [66]. Thus, the indoor temperature will not fluctuate very large suddenly although heat supply is less than required value sometimes. Then, it is just important for accumulative heat supply within a period of time to equals accumulative heating demand [29].

Heat loss appears within mass flow which results in a temperature drop because of temperature difference between flowing water and the surroundings. Li et al. [34] firstly estimated the outlet temperature of district heating using historic temperature of inlet considering total time of flow from inlet. Secondly, temperature drop due to heat losses is calculated by

$$\tau_{b,t}^{PS,out} = \tau_t^{am} + \left(\tau_{b,t}^{\prime PS,out} - \tau_t^{am}\right) \times exp\left[-\frac{\lambda_b \Delta t}{A_b \rho c}\left(\gamma_{b,t} + \frac{1}{2} + \frac{S_{b,t} - R_{b,t}}{ms_{b,t-\gamma_{b,t}}^{pipe} \Delta t}\right)\right] \tag{6}$$

$$\tau_{b,t}^{PR,out} = \tau_t^{am} + \left(\tau_{b,t}^{\prime PR,out} - \tau_t^{am}\right) \times exp\left[-\frac{\lambda_b \Delta t}{A_b \rho c}\left(\gamma_{b,t} + \frac{1}{2} + \frac{S_{b,t} - R_{b,t}}{ms_{b,t-\gamma_{b,t}}^{pipe} \Delta t}\right)\right] \tag{7}$$

where $\tau_{b,t}^{PS,out}/\tau_{b,t}^{PR,out}$ is the mass flow temperature concerning temperature drop at pipeline b outlet in supply/return network at period t. $\tau_{b,t}^{\prime PS,out}/\tau_{b,t}^{\prime PR,out}$ is the mass flow temperature without temperature drop at pipeline b outlet in supply/return network at period t, τ_t^{am} is the ambient temperature at period t, λ_b is heat transfer coefficient for pipeline b, Δt is time interval per period, A_b is cross-sectional area for pipeline b, ρ means water density, c is specific heat capacity of water, $\gamma_{b,t}$ is numbers of time periods indicating time delays of pipe b at period t associating changes in temperature, $R_{b,t}/S_{b,t}$ is the coefficient variables of pipe b at period t with historic flow mass, $ms_{b,t}^{pipe}/mr_{b,t}^{pipe}$ is mass flow rate of pipe b in supply/return network at period t.

Similar to Ohm law, heat loss along pipes could show as follows [26]:

$$h_f = K\dot{m}\left|\dot{m}\right| \tag{8}$$

where K is resistance coefficient for each pipe, $\dot{m}$ means mass flow rate within each pipeline, h_f is vector of heat loss within pipes. It indicates hydraulic characteristics of pipelines.

4.4 Mass flow continuity

According to continuity law, for the incompressible water flow, whole mass flow rate into each node is zero [34]. In supply and return networks, the nodal continuity of mass flow could be described as follows:

$$\sum_{b \in S_i^{pipe+}} ms_{b,t}^{pipe} - \sum_{b \in S_i^{pipe-}} ms_{b,t}^{pipe} = \sum_{j \in S_i^{HES}} m_{j,t}^{HS} - \sum_{l \in S_i^{HS}} m_{l,t}^{HES} \ \forall_i \in \tau^{nd}, t \in \tau \tag{9}$$

$$\sum_{b \in S_i^{pipe+}} mr_{b,t}^{pipe} - \sum_{b \in S_i^{pipe-}} mr_{b,t}^{pipe} = \sum_{l \in S_i^{HS}} m_{l,t}^{HES} - \sum_{j \in S_i^{HES}} m_{j,t}^{HS} \ \forall_i \in \tau^{nd}, t \in \tau \tag{10}$$

where $S_i^{pipe+/-}$ is the set of indices of pipes starting/ending at node i, $m_{j,t}^{HS}$ is the heat station's mass flow rate j at period t, $m_{l,t}^{HES}$ is the mass flow rate of heat exchanger station l at period t, τ^{nd} is the set of indices of nodes in heat network.

4.5 Pressure loss

Based on the Darcy-Weisbach equation [62], because of friction along pipelines the mass flow's pressure loss is proportional to mass flow rate's square [34]:

$$\mathrm{pr}^{S}_{n1,t}-pr^{S}_{n2,t}=\mu_b\left(ms^{pipe}_{b,t}\right)^2, \mathrm{pr}^{R}_{n2,t}-pr^{R}_{n1,t}=\mu_b\left(mr^{pipe}_{b,t}\right)^2\ \forall b\in\tau^{pipe}, n1=Nd^{PF}_{b}, n2=Nd^{PT}_{b}, t\in\tau \tag{11}$$

where $pr^{S}_{n,t}/\mathrm{p}r^{R}_{n,t}$ is pressure head of supply/return network at period t at node n, μ_b is the pressure loss coefficient for water pipe b, Nd^{PF}_{b} is the index of initial node of pipe b, Nd^{PT}_{b} is the ending node index for pipe b.

The pressure drop $\Delta\mathrm{p}$ could be also defined by [57].

$$\Delta\mathrm{p}=\mathrm{f}\frac{L}{D^5}\frac{8\dot{m}^2}{\rho\pi^2} \tag{12}$$

where f means Darcy friction factor, L represents pipe length, D means diameter of pipe, $\dot{m}$ stands for the mass flow rate within each pipe, ρ means water density. However, Sartor et al. [48] neglected pressure drop in each cell of network model.

4.6 Electricity system model

AC power flow model contains Ohm law, Kirchhoff current and voltage laws. Electricity network could be modelled using AC power flow [26,60] below:

$$\Delta P_i=P^{SP}_i-V_i\sum_{j\varepsilon i}V_j\left(G_{ij}cos\theta_{ij}+B_{ij}sin\theta_{ij}\right) \tag{13}$$

$$\Delta Q_i=Q^{SP}_i-V_i\sum_{j\varepsilon i}V_j\left(G_{ij}cos\theta_{ij}-B_{ij}sin\theta_{ij}\right) \tag{14}$$

where P is electrical real power, V means voltage amplitude, G_{ij} represents real part of element (i, j) for node admittance matrix, θ_{ij} is voltage angle difference for node i and j (rad), B_{ij} is the imaginary part of element (i, j) for node admittance matrix, i and j mean node number of electricity or heating network.

4.7 Hydraulic model of heating network

Heating network could be modelled by a thermal model and a hydraulic model [26,27] using mass flow rates, pressures, heat power, supplying and return temperatures. Hydraulic model expresses a relationship between pressures and mass flow rates for a heating network. Similar to Kirchhoff current and voltage laws, flow continuity and loop pressure equation are shown as follows, respectively:

$$\mathrm{A}\dot{m}=\dot{m}_q \tag{15}$$

$$\mathrm{B}h_f=0 \tag{16}$$

where A means a network incidence matrix, $\dot{m}$ represents a mass flow rate for each pipeline, $\dot{m}_q$ is a injected mass flow rate at each node, B stands for a loop incidence matrix, h_f means a vector of heat loss within pipes.

4.8 Numerical simulations

Matlab/Simulink is one of the most popular advanced computational technique and methodology for present years to model different types of district energy networks combining with advanced energy technologies and sustainable energy systems. Seen from Table 2, almost half of literature studied energy network using Matlab/Simulink [15,26,29–32,34, 39,49,51–53,57,59,67–72].

Jie et al. [29] employed *fmincon* function of Matlab to optimize the nonlinear programming problem for IDH operation. Carpaneto et al. [39] developed an optimiser XEMS13 to obtain production profiles and operational costs and shares based on inputs including plant configuration, components database and time profiles. Vesterlund et al. [49] developed the model for a meshed DH networks simulation using MATLAB/Simulink environment. Complex network configurations could be indicated by associating few types of blocks in a custom diagram. Vesterlund et al. [51] employed Simulink environment to simulate heat and mass flows distribution within a network for calculating the overall thermal energy; meanwhile, ReMIND software was employed to optimize a required heat production in order to arrange a schedule for the plants and fuels, which could achieve minimal operating cost.

TRNSYS is another main simulation tool employed in evaluating and optimizing the performance of energy network including its component such as GSHP [36,37,73], duct ground heat storage [46], pipe and duct [48], borehole thermal energy storage [73–79]. Sartor et al. [48] used TRNSYS Type 31 according to a Lagrangian approach to simulate the pipe and duct. Safa et al. [36] employed Type 668 GSHP module to develop heating/cooling performance according to source temperatures and building loads.

Except Matlab or Simulink and TRNSYS, there are other software to simulate all types of district energy networks e.g. Modelica [80–82], SiCEDS simulator [17], EnergyPro [83], IDA-ICE [84,85], LabVIEW [86], TERMIS [87], EES (Engineering Equation Solver) [88]. In addition, associating with different types of software, such as TERMIS, EnergyPLAN and Matlab [14,15,89], PSS SIGNAL and FICO Xpress [50] Matlab and Excel VBA [31], Matlab and EnergyPlus [30], TRNSYS and GenOpt [41], Matlab/Simulink (Simscape) and EBSILON [90], TRNSYS and Building Controls Virtual Test Bed (BCVTB) [91], appears to be a novel trend to develop advanced models or optimization algorithms to solve more complex problems for district energy networks.

4.9 Experimental study

Physical experimental investigation aims generally to validate mathematical and numerical models. In addition, it is to provide physical experimental support to parametrically analytical research (introduced in Section 4.5). There were few experimental investigations on the performance of energy network have already carried out [35,36,48,65,67,92].

Safa et al. [36] evaluated experimentally cooling and heating performance for the GSHP system with coupled horizontal ground-loop pipelines via monitoring in summer and winter. Sartor et al. [48] built an experimental test rig in a Thermodynamics Lab of University of Liege. The ambient temperature near the pipe, and inlet and outlet water temperatures could be measured by T-thermocouples. The flow rate of volume was tested by the mechanical volume flow meter with impulsions, whose nominal flow rate was 6 m^3/h. The data acquisition system is a NI cDAQ 9188, which is coupled with NI9213 for a thermocouple measurement and with NI 9401 for pulse counting. For this test rig, the flow velocity and temperature step could be studied.

4.9.1 Validation of numerical models

Safa et al. [36] validated the TRNSYS model via comparing the simulation results of daily cooling and heating demand/GSHP output as a function of mean daily outside temperature with GSHP experimental data. Franco et al. [67] used the experimental data obtained from the remote monitoring system to validate the dynamic simulation model, which is the fixed-step time-series model, under a Matlab/Simulink environment for district heating combined with CHP plant.

4.10 Parametric study

Parametric sensitivity analysis aims to evaluate various parameters dependence in the performance of energy network and then to seek the potential possibilities of optimization. Table 3 demonstrates diverse parametric analysis study and its corresponding study results for the latest years.

alt-text: Table 3

Table 3

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To preview the actual presentation of the table, please view the Proof.

Comparison of parametric study and its corresponding investigation results.

Parameter	Key Results
Effect of Lambda-value (thermal conductivity)	Heat loss between the heating plant and the consumer regardless of the energy form e.g. CHP, surplus heat from industry, waste, gas, solar heat etc. is reduced using smaller lambda-value [13]
Effect of weather conditions (e.g. environment temperature)	Environment temperature affects heat loss to some extent [47]; outdoor temperature is the most significant parameter to affect heat supply [29]; annual weather condition differences could essentially influence performance of solar district heating system performance [77]
Effect of delay time deviation	There is a large impact from just a little delay time deviation on stage of quick and large temperature changes [47]
Effect of relative attenuation degree	Relative attenuation degree mainly affects the accuracy at relatively stable stage [47]
Effect of ground temperature fluctuation	The influence of ground temperature fluctuation on water temperature is not large, therefore, it can be ignored [47]
Effect of heat (thermal) loss	It has a large effect on temperature prediction [47]; heat losses for insulated pipe have a tiny effect on outlet temperature of pipeline particularly for a short length of pipe [48]; fuel costs are just influenced by heat losses in district heating network (DHN) [52]; thermal losses influence mass flow rates and associated enthalpy flows [57]
Effects of hydraulic dispersion, thermal diffusion and axial heat transmission	Their effects could be neglected [47]
Effect of unsteady-state term of temperature distribution of water	It has an effect on dynamic parameters of district heating networks [47]
Effect of condenser outlet temperature	It affects significantly COP of heat pump [36]
Effect of ground temperature	Performance of GSHP slightly deteriorated because of a lower ground temperature near the loop [36]
Effect of soil temperature	The soil temperature's spatial distribution affects performance of COP [93]
Effect of pipe thickness	Thermal inertia is influenced by pipe thickness [48]
Effect of pipe thermal inertia	Thermal inertia of pipe has an obvious impact on temperature profile including response of outlet pipe, except when the fluid velocity is very low [48]; effect of thermal inertia decreases when pipe diameter rises [48]
Effect of level of complexity	The complexity level for a district heating network influences pattern of distribution of hot water [49]
Effect of pumping power	Impact of pumping power terms on whole operating cost is minor [49]
Effect of changed temperature limit	Return temperature could influence obtained optimal supplying temperature and flow rate [50]

Effect of DH operating strategy	It has a significant effect on annual energy performance and equivalent annual cost (EAC) [50]; operating strategies have little effect on annual heat loss costs for DH systems [29]
Effect of pipe diameters	Pipe diameters have the effect on pressure loss in DH and therefore on pumps' electrical energy consumption [50]
Effect of heat source	The heat source has the influence on optimal solution of flow rate and supply temperature during operation, therefore, on DH pump energy consumption and heat losses [50]
Effect of heat carrier flow rate	It could affect the electrical energy consumption of pumps [50]; generally mass flow rate could not influence fuel costs/heat losses obviously except at some discrete values [52]
Effect of temperature difference between supply and return pipes	When temperature difference between supply and return pipes increases, annual total energy consumption and equivalent annual cost will be decreased [50]
Effect of power load	Power load has no obvious influence for determining peak boilers' location [33]
Effect of pumping costs	In the sample network, total costs including fuel cost plus pumping cost are slightly affected by pumping costs [52]
Effect of supply temperature	Supply temperatures influence pumping costs significantly due to higher supply temperature resulting in lower mass flow and pressure drop [52]; higher supply water temperature will have unfavourable effect on heating pipes and insulation materials [29]
Effect of heating parameters	Heating parameters have little influence on heat sources' operating cost if the heat supply is constant [29]
Effect of dynamics of temperature variation	The temperature variation dynamics combined with hot water flow have obvious effects on the DH network operation [34]
Effect of groundwater	Groundwater flow presence could affect the thermal response of a borefield system [94]
Effect of the heat from radiators to indoor air	Heat from radiators to indoor air changes, which result in indoor temperatures changing, then influence the heating network [26]
Effect of thermal and hydraulic processes	Slow thermal process influences economic operation more than hydraulic process [26]
Effect of coupling component outage	Coupling component outage influences both electricity and heat generations [26]
Effect of different conversion components	Heat and electricity loads across heat, gas and electricity networks could be shifted by diverse conversion components, which then affects the operation of networks, e.g., voltage, temperature and pressure drop and losses [31]
Effect of constraints	Constraints on heating network layout affect optimal design and energy system operation [56]; commonly ignored constraints on CHP operation will result in obviously more reliance on district heating network [56]; electrical grid constraints have the significant effect on optimal solutions particularly renewable energy use at high level [30]

There have been lots of important parameters including lambda-value, environment temperature (including ground temperature and its fluctuation, soil temperature), delay time deviation, relative attenuation degree, heat (thermal) loss, thermal diffusion, hydraulic dispersion and axial heat transmission, unsteady-state term of temperature distribution of water, outlet temperature of condenser, pipe thickness, thermal inertia of the pipe, level of complexity, pumping power, changing temperature limit, DH operation strategy, pipe diameters, heat source, flow rate of heat carrier, temperature difference between supplying and return pipelines, power load, pumping costs, supply temperature, heating parameters, dynamics of temperature variation, groundwater, heat from radiators to building indoor air, thermal and hydraulic processes, coupling component outage, different conversion components, and constraints.

It is found that the environment temperature influences heat loss to some extent [47]. Outdoor temperature is the most significant parameter affecting heating supply [29]. However, effect of ground temperature on the water temperature is not obvious and could be neglected [47]. Unsteady-state term of temperature distribution of water has an impact on dynamic parameters of DH network [47]. Condenser outlet temperature will influence obviously COP of heat pump, and then DH network [36]. The GSHP performance slightly got worse because of a lower ground temperature nearby the loop [36]. Spatial distribution of soil temperature affects COP performance [93]. Changing return temperature limit could influence obtained optimal supplying temperature and flow rate [50]. To increase temperature difference between supplying and return pipelines will decrease total annual energy consumption and annual equivalent cost [50]. Supply temperature could affect pumping costs obviously because of high supplying temperature causing lower pressure drop and mass flow [52]. In addition, higher supply water temperature has an unfavourable effect on heating pipes and insulation materials [29]. Temperature variation dynamics integrated with hot water flow could have strong effects on DH network operation [34].

Heat loss between the heating plant and the consumer will be reduced with decreasing of lambda-value (thermal conductivity) [13]. Heat (thermal) loss has a large effect on temperature prediction [47]. However, the heat losses for the insulated pipe have a modest effect on pipeline outlet temperature, particularly a short length of pipe [48]. Fuel costs are just impacted by thermal losses in DH network [52]. Thermal losses will affect mass flow rates and associated enthalpy flows [57]. Pipe thermal inertia could have a strong effect on temperature profile e.g. response of the outlet pipe [48]. The impact of thermal inertia will decrease when pipe diameter increase [48].

The complexity level for a DH network affects pattern of hot water distribution [49]. DH operation strategy has a significant effect on annual energy performance and annual equivalent cost [50]. However, different conclusion is drawn that operation strategies have slight effect on annual thermal loss costs for DH networks [29].

Heat source has the effect on optimal solution of flow rate and supplying temperature during operating, thus upon DH pump energy consumption and thermal losses [50]. Heat parameters have slight influence on heat sources' operation cost if heat supply is constant [29]. The heat from radiators to indoor air in buildings changes, which lead to indoor temperatures changing, then affect the heating network [26]. Normally, slow heat process influences economic operation more than hydraulic process [26].

Coupling component outage influences both of heat and electricity generations [26]. Heat and electricity loads across heat, gas and electricity networks could be shifted by diverse conversion components, which then affects the operation of networks e.g. voltage, temperature and pressure drop and losses [31].

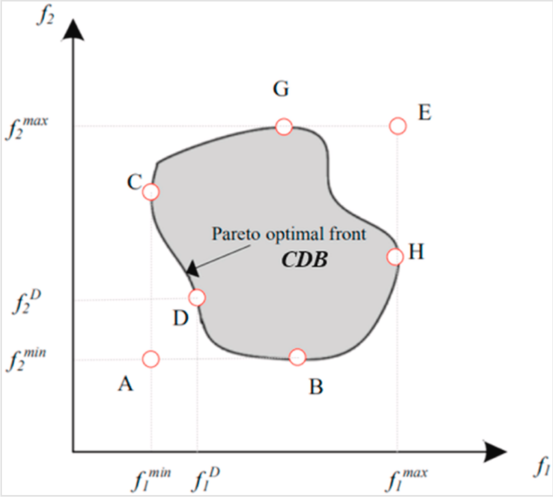
Commonly ignored constraints on CHP operation result in evidently more reliance on DH systems [56]. Constraints on DH layout affect optimal design and energy system operating [56]. Constraints on electrical grid have the obvious effect on the optimal solutions especially renewable energy use at high level [30]. In addition, the DH system constraints e.g. energy balance [95], time, site constraints, energy systems constraints e.g. cogeneration and storage constraints [95], and control strategies including disturbance and operating characteristics [68] will to some extend determine those effects as mentioned above [26].

5 Discussion

Optimization for district energy network (DEN) performance refers to optimal variables including supply temperature [49,50]), flow rate [50], total energy consumption and costs [29,50,52], storage capacity [39], energy network layouts [56] etc. Falke et al. proposed the criteria for selection of the lower (e.g., costs, CO_2 equivalents emissions) or upper bounds, which is based on multi-objective optimization model, i.e., integrated economic and ecological optimization [55]. Kuriqi et al. used Pareto-optimal front (see Fig. 7) to seek proper trade-offs between hydropower and ecological objectives, whose functions include maximal energy production and minimal flow alteration [97]. The algorithms for optimization of district energy network mainly include the hybrid evolutionary-MILP (mixed integer linear program) [49,54], genetic algorithm [52,53], etc.

alt-text: Fig. 7

Fig. 7



Pareto optimization for two-objective conflict: f_1 and f_2 would represent energy production and flow alteration [97].

Some limitations of review methodology and present study that conflicts with other work should be noted. First, the review was limited to articles published mainly last 10 years. Second, the review focused on the scientific and technical research, economic things were excluded. Third, this review focused on DEN performance evaluation and optimization, unlike the following review on district heating study: Mazhar et al. did an overview from economic and social aspects of district heating, presented the legislation, technological framework and policies with linkage to basic characteristics of grids [20]. Lund et al. described the contemporary developments and findings relevant to different elements required in the future 4G district heating systems [21]. Werner reviewed the current conditions of district heating and cooling, particularly providing deeper insights into European situation, from the point of view of supply, technical, market, institutional, environmental, and future contexts [22].

It is very important to integrate renewable energy sources, waste heat recovery into DEN, which could reduce the building sector environmental impact, achieve the sustainability goals and has very little environmental impacts, e.g., hydropower [97], photovoltaic [98], waste heat from coke oven [99]). It is also the most profitable and energy efficient solutions from the long-term point of view. In addition, district heating based on CO_2 heat pumps or heat pumps coupled with sea heat exchangers was the new trend and profitable solution [100,101].

The main disadvantages of DEN are including that the initial investment and maintenance cost is very large; the local government needs to provide the financial support and detailed plan and design for DEN before it constructs. The research gap of DEN is how to integrate efficiently and smoothly several energy systems and renewable energy resources into DEN. The main challenge of DEN technology mentioned by previous literature is, e.g., the same pipes for DEN are not able to provide both heating and cooling simultaneously to different buildings [102].

6 Conclusions

A state-of-art review on the present district energy network performance evaluation and optimization, particularly focusing on heat network combining with electricity and gas networks, with advanced technologies, was reported in this article. The main scientific and valuable conclusions are as follows:

1) Compared with current representative projects for district energy network (DEN), the best overall performance should combine several integrated energy sources utilization with advanced technologies, such as the novel project of balanced energy network (BEN), which contains borehole, cold water heat networks, water source heat pump, smart thermal storage, smart grid technologies e.g. demand side response (DSR). BEN is the next generation energy network with ambient temperature, which is far less than 4th generation district heating network with 50 °C–60 °C.
2) It is very necessary and significant to investigate the mathematicall modelling of DEN, including heat balance, continuity of mass flow, pressure loss, electricity system model, and hydraulic model etc., which could evaluate the performance of individual and whole energy system for district energy network and then seek the potential possibilities of optimization.
3) Almost half of the reviewed articles in this work studied energy network using Matlab/Simulink, which is recently the most popular simulation environment.
4) More than 30 factors influencing district energy performance were investigated and assessed. Impacts of those factors on energy network performance were completely diverse, depending upon constraints of system, site and time, and the interaction between variable factors.
5) The future DEN development will focus on advanced optimization algorithms and strategies (soft technologies) combining with cutting-edge renewable energy supply, smart energy storage, smart energy transfer and energy-efficient application (hard technologies).

7 Future work

Our project of Balanced Energy Networks (BEN) funded by Innovate UK has been currently investigating and developing by the present authors through individual and whole system modeling and simulation. Practical testing and evaluation on BEN system performance will be performed in the future.

Q3 Uncited reference

[~~96~~].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was partially supported by the Innovate UK project Balanced Energy Networks (BEN), Overseas High-level Youth Talents Program of China (China Agricultural University, China, Grant No. 62339001), Major Science and Technology Innovation Fund 2019 of Shandong Province (Grant No. 2019JZZY010703), Science and Technology Cooperation – Sino-Malta Fund 2019: Research and Demonstration of Real-time Accurate Monitoring System for Q2 Early-stage Fish in Recirculating Aquaculture System (AquaDetector, Grant No. SQ2019YFE010142), China Agricultural University Excellent Talents Plan (Grant No. 31051015). This work was made possible by the technical and intellectual contributions of the members of the BEN Consortium. The authors are also very grateful to the referees who provide valuable and positive comments.

Nomenclature

A:	network incidence matrix
A_b:	cross-sectional area of pipeline b
A_h:	area of heat exchanger
a_s, b_s:	coefficients for calculating the heat transfer from one piece of radiator to rooms
B:	loop incidence matrix
B_{ij}:	imaginary part of element (i, j) in node admittance matrix
c:	specific heat capacity of water
D:	diameter of the pipe

f:	Darcy friction factor
G_{ij}:	real part of element (i, j) in node admittance matrix
h_f:	vector of heat loss within pipes
i, j:	number of pipe sections with same diameter in the primary and secondary heating networks, respectively; node number of the electricity or heating network
K:	resistance coefficient of each pipe
K_h:	heat transfer coefficient of heat exchanger
l, L:	pipe length
$ms_{b,t}^{pipe}/mr_{b,t}^{pipe}$:	mass flow rate of pipeline b in the supply/return network at period t
$m_{j,t}^{HS}$:	mass flow rate of heat station j at period t
$m_{l,t}^{HES}$:	mass flow rate of heat-exchanger station l at period t
$\dot{m}$:	mass flow rate within each pipe
$\dot{m}_q$:	injected mass flow rate at each node
n, m:	total number of pipe sections with same diameter in the primary and secondary heating networks
Nd_b^{PF}:	index of starting node of pipeline b
Nd_b^{PT}:	index of ending node of pipeline b
n_s:	pieces of radiators
P:	electrical real power
$\mathrm{pr}_{n,t}^S/\mathrm{pr}_{n,t}^R$:	pressure head of the supply/return network at node n at period t
Q_d:	heat demand of consumers
Q_{lp}:	heat loss of the primary heating network
Q_{ls}:	heat loss of the secondary heating network
Q_s:	heat supply
R_{b1}, R_{b2}:	heat resistance for insulation materials of two parallel pipes (i.e. supply and return water pipes) buried in the ground
$R_{b,t}/S_{b,t}$:	coefficient variables of pipeline b at period t associated with the historic flow mass
R_c:	additional heat resistance
R_t:	ground heat resistance
$S_i^{pipe+/-}$:	set of indices of pipelines starting/ending at node i
t_g:	ground surface temperature
t_n:	indoor temperature
t_{pr}:	primary return water temperature
t_{ps}:	primary supply water temperature
t_{sr}:	secondary return water temperature
t_{ss}:	secondary supply water temperature
V:	voltage amplitude
τ:	a period of time
β:	additional heat loss coefficient caused by accessories, compensators, valves etc.
Δp:	pressure drop
Δt:	time interval per period
Δt_m:	logarithmic mean temperature difference
$\gamma_{b,t}$:	numbers of time periods denoting time delays of pipeline b at period t associating changes in temperature
τ^{nd}:	set of indices of nodes in the heating network
τ_t^{am}:	ambient temperature at period t
$\tau_{b,t}^{PS,out}$:	$/\tau_{b,t}^{PR,out}$ mass flow temperature concerning temperature drop at the outlet of pipeline b in the supply/return network at period t
$\tau_{b,t}^{/PS,out}$:	$/\tau_{b,t}^{/PR,out}$ mass flow temperature without temperature drop at the outlet of pipeline b in the supply/return network at period t
λ_b:	heat transfer coefficient of pipeline b
ρ:	density of water
μ_b:	coefficient of pressure loss in water pipeline b

θ_{ij}: voltage angle difference of node i and j (rad)

Abbreviation

AC: alternating current
BEN: balanced energy network
CHP: combined heat and power
CHPD: combined heat and power dispatch
COP: coefficient of performance
CSE: centre for sustainable energy
DEN: district energy network
DH: district heating
DHN: district heating network
DHS: district heating system
DNO: district network operator
DSM: digital surface model
DSR: demand side response
EAC: equivalent annual cost
GSHP: ground-source heat pump
IDH: indirect district heating
LHD: linear heat density
MCDA: multicriteria decision analysis
MINLP: mixed integer non-linear programming
PHLC: pumping and heat loss cost
TES: thermal energy storage

References

The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

[1] IEA (International Energy Agency). Transition to sustainable buildings: strategies and opportunities to 2050. 2013. France www.iea.org.

[2] Wang Y., Kuckelkorn J., Zhao F.Y., Spliethoff H., Lang W. A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings. Renew Sustain Energy Rev 2017;72:1303–1319.

[3] Anderson J.E., Wulfhorst G., Lang W. Energy analysis of the built environment – a review and outlook. Renew Sustain Energy Rev 2015;44:149–158.

[4] Energy and Climate Change (HM Government). Government report: carbon plan. 2008. 2017 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47621/1358-the-carbon-plan.pdf. [Accessed 20 April 2017].

[5] Perez-Lombard L., Ortiz J., Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–398.

[6] Sayegh M.A., Danielewicz J., Nannou T., Miniewicz M., Jadwiszczak P., Piekarska K., et al. Trends of European research and development in district heating technologies. Renew Sustain Energy Rev 2017;68:1183–1192.

[7] Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F., et al. 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11.

[8]

P.L. Youngerhttp://www.etp-scotland.ac.uk/KnowledgeExchange/IndustryDoctorates/Project58Renewableheatnetworks.aspx, 2018s , 9 April 2018.

[9] Song W.H., Wang Y., Gillich A., Ford A., Hewitt M. Modelling development and analysis on the balanced energy networks (BEN) in London. Appl Energy 2019;233–234:114–125.

[10] 2018. http://gtr.rcuk.ac.uk/projects?ref=102624; 2018. [Accessed 9 April 2018].

[11] 2018. http://www.strath.ac.uk/sustainablestrathclyde/chp/; 2018. [Accessed 9 April 2018].

[12] 2018. https://www.cse.org.uk/projects/view/1314; 2018. [Accessed 9 April 2018].

[13] 2018. https://www.logstor.com/; 2018. [Accessed 9 April 2018].

[14] Mohammadi S. Conversion of existing district heating grids to low-temperature operation and extension to new areas of buildings PhD Thesis. Aalborg University; 2016.

[15] Lund R., Mohammadi S. Choice of insulation standard of pipe networks in 4th generation district heating systems. Appl Therm Eng 2016;98:256–264.

[16] 2018. http://www.minibems.com/what-is-minibems/; 2018. [Accessed 9 April 2018].

[17] Lomax, N., Barrett, M. Developing a city energy modelling tool and approach. ECEEE Summer Study Proceedings2017;851-856.

[18] 2018. http://www.energysavingtrust.org.uk/blog/paving-road-smart-cities; 2018. [Accessed 9 April 2018].

[19] 2018. http://www.energysavingtrust.org.uk/business/data-and-insight/siceds; 2018. [Accessed 9 April 2018].

[20] Mazhar A., Liu S., Shukla A. A state of art review on the district heating systems. Renew Sustain Energy Rev 2018;98:420–439.

[21] Lund H., Ostergaard P., Chang M. etc. The status of 4th generation district heating: research and results. Energy 2018;164:147–159.

[22] Werner S. International review of district heating and cooling. Energy 2017;137:617–631.

[23] Lund H., Duic N., Ostergaard P., Mathiesen B. Future district heating systems and technologies: on the role of smart energy systems and 4th generation district heating. Energy 2018;165A:614–619.

[24] Rismanchi B. District energy network (DEN), current global status and future development. Renew Sustain Energy Rev 2017;75:571–579.

[25] Lizana J., Ortiz C., Soltero V.M., Chacartegui R. District heating systems based on low-carbon energy technologies in Mediterranean areas. Energy 2017;120:397–416.

[26] Pan Z., Guo Q., Sun H. Interactions of district electricity and heating systems considering time-scale characteristics based on quasi-steady multi-energy flow. Appl Energy 2016;167:230–243.

[27] Liu X., Wu J., Jenkins N.A. Bagdanavicius. Combined analysis of electricity and heat networks. Appl Energy 2016;162:1238–1250 a.

[28] Liu X. Combined analysis of electricity and heat networks. Cardiff University; 2013.

[29] Jie P., Zhu N., Li D. Operation optimization of existing district heating systems. Appl Therm Eng 2015;78:278–288.

[30] Morvaj B., Evins R., Carmeliet J. Optimization framework for distributed energy systems with integrated electrical grid constraints. Appl Energy 2016;171:296–313 b.

[31] Liu X., Mancarella P. Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems. Appl Energy 2016;167:336–352 b.

[32] Ghadimi P., Kara S., Kornfeld B. The optimal selection of on-site CHP systems through integrated sizing and operational strategy. Appl Energy 2014;126:38–46.

[33] Wang H., Lahdelma R., Wang X., Jiao W., Zhu C. Analysis of the location for peak heating in CHP based combined district heating systems. Appl Therm Eng 2015;87:402–411.

[34] Li Z., Wu W., Shahidehpour M., Wang J., Zhang B. Combined heat and power dispatch considering pipeline energy storage of district heating network. IEEE Transactions on Sustainable Energy 2016;7–1:12–22.

[35] Comodi G., Lorenzetti M., Salvi D., Arteconi A. Criticalities of district heating in Southern Europe: lesson learned from a CHP-DH in Central Italy. Appl Therm Eng 2017;112:649–659.

[36] Safa A.A., Fung A.S., Kumar R. Heating and cooling performance characterisation of ground source heat pump system by testing and TRNSYS simulation. Renew Energy 2015;83:565–575.

[37] Allaerts K., Koussa J. Al, Desmedt J., Salenbien R. Improving the energy efficiency of ground-source heat pump systems in heating dominated school buildings: a case study in Belgium. Energy Build 2017;138:559–568.

[38] Lucia U., Simonetti M., Chiesa G., Grisolia G. Ground-source pump system for heating and cooling: review and thermodynamic approach. Renew Sustain Energy Rev 2017;70:867–874.

[39] Carpaneto E., Lazzeroni P., Repetto M. Optimal integration of solar energy in a district heating network. Renew Energy 2015;75:714–721.

[40] Tian Z., Zhang S., Deng J. etc. Large-scale solar district heating plants in Danish smart thermal grid: developments and recent trends. Energy Convers Manag 2019;189:67–80.

[41] Tian Z., Perers B., Furbo S., Fan J. Thermo-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic though collectors in series. Energy Convers Manag 2018;165:92–101.

[42] Tian Z., Perers B., Furbo S., Fan J. Annual measured and simulated thermal performance analysis of a hybrid solar district heating plant with flat plate collectors and parabolic though collectors in series. Appl Energy 2017;205:417–427.

[43] Tian Z., Perers B., Furbo S., Fan J. Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating. Energy 2018;142:130–138.

[44] Unternaehrer J., Moret S., Joost S., Marechal F. Spatial clustering for district heating integration in urban energy systems: application to geothermal energy. Appl Energy 2017;190:749–763.

[45] 2018. http://www.4dh.eu/news/110-lowering-the-heat-loss-with-state-of-the-art-pipes; 2018. [Accessed 9 April 2018].

[46] Pahud D., Hellstrom G., Mazzarella L. Heat storage in the ground: duct ground heat storage model for TRNSYS (TRNVDST). User manual for the October 1996 version. Switzerland: EPFL – LASEN; 1996.

[47] Zheng J., Zhou Z., Zhao J., Wang J. Function method for dynamic temperature simulation of district heating network. Appl Therm Eng 2017;123:682–688.

[48] Sartor K., Dewalef P. Experimental validation of heat transport modelling in district heating networks. Energy 2017;137:961–968.

[49] Vesterlund M., Toffolo A., Dahl J. Optimization of multi-source complex district heating network, a case study. Energy 2017;126:53–63.

[50] Pirouti M., Bagdanavicius A., Ekanayake J., Wu J., Jenkins N. Energy consumption and economic analyses of a district heating network. Energy 2013;57:149–159.

[51] Vesterlund M., Dahl J. A method for the simulation and optimization of district heating systems with meshed networks. Energy Convers Manag 2015;89:555–567.

[52] Fang T., Lahdelma R. Genetic optimization of multi-plant heat production in district heating networks. Appl Energy 2015;159:610–619.

[53] Wang J., Zhou Z., Zhao J. A method for the steady-state thermal simulation of district heating systems and model parameters calibration. Energy Convers Manag 2016;120:294–305.

[54] Mertz T., Serra S., Henon A., Reneaume J. A MINLP optimization of the configuration and the design of a district heating network: academic study cases. Energy 2016;117:450–464.

[55] Falke T., Krengel S., Meinerzhagen A., Schnettler A. Multi-objective optimization and simulation model for the design of distributed energy systems. Appl Energy 2016;184:1508–1516.

[56] Morvaj B., Evins R., Carmeliet J. Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout. Energy 2016;116:619–636 a.

[57] Vesterlund M., Toffolo A., Dahl J. Simulation and analysis of a meshed district heating network. Energy Convers Manag 2016;122:63–73.

[58] Sheng X., Duanmu L. Energy saving factors affecting analysis on district heating system with distributed variable frequency speed pumps. Appl Therm Eng 2017;121:779–790.

[59] Pan Z., Guo Q., Sun H. Feasible region method based integrated heat and electricity dispatch considering building thermal inertia. Appl Energy 2017;192:395–407.

[60] Zhang B., Yan Z. Advanced electric power network analysis. Cengage Learning Asia; 2010.

[61] Balic D., Maljkovic D., Loncar D. Multi-criteria analysis of district heating system operation strategy. Energy Convers Manag 2017;144:414–428.

[62] Rohsenow W.M., Hartnett J.P., Ganic E.N. Handbook of heat transfer fundamentals. New York, NY, USA: McGraw-Hill; 1985.

[63] Wang Y., You S., Zhang H., Zheng W., Zheng X., Miao Q. Hydraulic performance optimization of meshed district heating network with multiple heat sources. Energy 2017;126:603–621.

[64] Yan A., Zhao J., An Q., Zhao Y., Li H., Huang Y.J. Hydaulic performance of a new district heating systems with distributed variable speed pumps. Appl Energy 2013;112:876–885.

[65] Zhou S., Li H., Gong P., Tian M. Hydraulic modelling of double-source and ring-shaped heating networks. Appl Therm Eng 2017;119:215–221.

[66] Turski M., Sekret R. Buildings and a district heating network as thermal energy storages in the district heating system. Energy Build 2018;179:49–56.

[67] Franco A., Versace M. Optimum sizing and operational strategy of CHP plant for district heating based on the use of composite indicators. Energy 2017;124:258–271.

[68] Marguerite C., Andresen G.B., Dahl M. Multi-criteria analysis of storages integration and operation solutions into the district heating network of Aarhus – a simulation case study. Energy 2018;158:81–88.

[69] Denarie A., Muschera M., Calderoni M., Motta M. Industrial excess heat recovery in district heating: data assessment methodology and application to a real case study in Milano, Italy. Energy

2019;166:170–182.

[70] Denarie A., Aprile M., Motta M. Heat transmission over long pipes: new model for fast and accurate district heating simulations. Energy 2019;166:267–276.

[71] Wang Y., You S., Zhang H. etc. Operation stability analysis of district heating substation from the control perspective. Energy Build 2017;154:373–390.

[72] Gustafsson J., Delsing J., Deventer J.V. Improved district heating substation efficiency with a new control strategy. Appl Energy 2010;87:1996–2004.

[73] Renaldi R., Friedrich D. Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK. Appl Energy 2019;236:388–400.

[74] Flynn C., Siren K. Influence of location and design on the performance of a solar district heating system equipped with borehole seasonal storage. Renew Energy 2015;81:377–388.

[75] Ciampi G., Rosato A., Sibilio S. Thermo-economic sensitivity analysis by dynamic simulations of a small Italian solar district heating system with a seasonal borehole thermal energy storage. Energy 2018;143:757–771.

[76] Rosato A., Ciervo A., Ciampi G., Sibilio S. Effects of solar field design on the energy, environmental and economic performance of a solar district heating network serving Italian residential and school buildings. Renew Energy 2019;143:596–610.

[77] Hirvonen J., Rehman H.U., Siren K. Techno-economic optimization and analysis of a high latitude solar district heating system with seasonal storage, considering different community sizes. Sol Energy 2018;162:472–488.

[78] Hirvonen J., Siren K. A novel fully electrified solar heating system with a high renewable fraction – optimal designs for a high latitude community. Renew Energy 2018;127:298–309.

[79] Rehman H.U., Hirvonen J., Siren K. Performance comparison between optimized design of a centralized and semi-decentralized community size solar district heating system. Appl Energy 2018;229:1072–1094.

[80] Schweiger G., Larsson P., Magnusson F., Lauenburg P., Velut S. District heating and cooling systems – framework for Modelica-based simulation and dynamic optimization. Energy 2017;137:566–578.

[81] Heijde B., Fuchs M., Tugores C.R. etc. Dynamic equation-based thermos-hydraulic pipe model for district heating and cooling systems. Energy Convers Manag 2017;151:158–169.

[82] Arce I., Lopez S., Perez S. etc. Models for fast modelling of district heating and cooling networks. Renew Sustain Energy Rev 2018;82(2):1863–1873.

[83] Kontu K., Rinne S., Junnila S. Introducing modern heat pumps to existing district heating systems – global lessons from viable decarbonizing of district heating in Finland. Energy 2019;166:862–870.

[84] Ashfaq A., Ianakiev A. Investigation of hydraulic imbalance for converting existing boiler based buildings to low temperature district heating. Energy 2018;160:200–212.

[85] Zhang L., Gudmundsson O., Thorsen J. etc. Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level. Energy 2016;107:431–442.

[86] Lazarevic S., Congradac V., Andelkovic A.S. etc. A novel approach to real-time modelling of the district heating substation system using LabVIEW. J Clean Prod 2019;217:360–370.

[87] Tunzi M., Boukhanouf R., Li H. etc. Improving thermal performance of an existing UK district heat network: a case for temperature optimization. Energy Build 2018;158:1576–1585.

[88]

Ommen T., Thorsen J., Markussen W. etc. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. Energy 2017;137:544–555.

[89] Askeland K., Bozhkova K.N., Sorknaes P. Balancing Europe: can district heating affect the flexibility potential of Norwegian hydropower resources? Renew Energy 2019;141:646–656.

[90] Dahash A., Mieck S., Ochs F., Krauz H. A comparative study of two simulation tools for the technical feasibility in terms of modeling district heating systems: an optimization case study. Simulat Model Pract Theor 2019;91:48–68.

[91] Schweiger G., Heimrath R., Falay B. etc. District energy systems: modelling paradigms and general-purpose tools. Energy 2018;164:1326–1340.

[92] Noussan M., Jarre M., Poggio A. Real operation data analysis on district heating load patterns. Energy 2017;129:70–78.

[93] Qian H., Wang Y. Modelling the interactions between the performance of ground source heat pumps and soil temperature variations. Energy for Sustainable Development 2014;23:115–121.

[94] Atam E., Helsen L. Ground-coupled heat pumps: Part 1 – literature review and research challenges in modelling and optimal control. Renew Sustain Energy Rev 2016;54:1653–1667.

[95] Dahl M., Brun A., Andresen G.B. Cost sensitivity of optimal sector-coupled district heating production systems. Energy 2019;166:624–636.

~~[96] Guelpa E., Barbero G., Sciacovelli A. etc. Peak-shaving in district heating systems through optimal management of the thermal request of buildings. Energy 2017;137:706–714.~~

[97] Kuriqi A., Pinheiro A.N., Sordo-Ward A., Garrote L. Flow regime aspects in determining environmental flows and maximizing energy production at run-of-river hydropower plants. Appl Energy 2019;256:113980.

[98] Novosel T., Puksec T., Duic N., Domac J. Heat demand mapping and district heating assessment in data-pour areas. Renew Sustain Energy Rev 2020;131:109987.

[99] Sun F., Li J., Fu L., Li Y. etc. New configurations of district heating and cooling system based on absorption and compression chillers driven by waste heat of flue gas from coke ovens. Energy 2020;193:116707.

[100] Calise F., Cappiello F.L., d'Accadia M.D., Vicidomini M. Energy efficiency in small districts: dynamic simulation and technoeconomic analysis. Energy Convers Manag 2020;220:113022.

[101] Calise F., Cappiello F.L., Vicidomini M., Robinson F.P. Water-energy nexus: a thermoeconomic analysis of polygeneration systems for small Mediterranean islands. Energy Convers Manag 2020;220:113043.

[102] Buffa S., Cozzini M., Antoni M.D., Baratieri M., Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. Renew Sustain Energy Rev 2019;104:504–522.

Highlights

- First review on performance for district energy network considering heating/cooling, electricity & gas.
- Various advanced technologies for energy network investigated via simulation/measurement.
- Parametric sensitivity analysis including diverse effects of 30+ parameters on energy performance.

- Comparison and evaluation on performance of different technologies applied in energy network.
- A novel next-generation energy network using several cutting-edge technologies developed in London.

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